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A MULTI-SCALE MODELLING SYSTEM OPERABLE IN CASE OF AN EMERGENCY – APPLICATION TO A FICTITIOUS ATTACK AGAINST A CRITICAL INFRASTRUCTURE

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Abstract: It is likely that potentially harmful to human health or the environment atmospheric releases can originate from accidents or malicious actions in built-up (industrial, harbour or urban) populated areas. Appropriate 3D models able to tackle such complex environments are now available and ready to be integrated in decision-support systems. This paper desribes the multi-scale flow and dispersion simulations that were run and provided to the rescue teams in the frame of an emergency exercise held on March 8, 2016 in a large city of France along the Mediterranean Sea. The modelling system implememented the most recent improvements of WRF and PMSS in a downscaling numerical chain. The exercise was carried out by several services, especially the firefighters and the local state authorities. The scenario was a fictitious attack implying a noxious dispersion in a semi-open public infrastructure. As commented on in the paper, the exercice was a practical demonstration that a state-of-the-art modelling system is nowadays more than ”of interest”, but an integral component of the preparedness and response in case of an emergency.

Key words: emergency exercise, meso-scale, urban scale, WRF, PMSS, decision-support system.

INTRODUCTION

Accidents affecting industrial facilities or malevolent activities plausibly perpetrated in urban districts (sabotage, terrorist attacks) can imply the release of hazardous gaseous or particulate materials into the air. These events are potential threats to both people health and the environment and a major subject of concern for the rescue teams and their local and national authorities. As built-up places are the most likely places for noxious releases and concentrate large populations, they deserve a particular attention.

In the same time, modelling the flow and dispersion in such areas is most often very complex due to the influence of the geography and topography (coastal area, rugged terrain…) and of the intricate buildings geometry in evolving meteorological conditions. Moreover, releases resulting from an industrial accident or a terrorist action are by essence poorly known (at least at the beginning of the event) and simulations on a very large area around the release point may be needed in order to provide a relevant answer to the authorities, wanting to know where dangerous areas, and also safe areas, are located. Therefore, reliable impact assessment of toxic releases generally requires an advanced 3D approach with high space and time resolution from the source of the release up to the largest extent of the affected area.

To address this critical issue, we have developed a multi-scale modelling chain for the atmospheric flow and dispersion simulations with the view to producing results in a moderate time (given appropriate computational resources). This paper describes the models embedded in our downscaling and upscaling system which is generic as its underlying principles are the same, irrespective of the dispersion situation, and flexible as the computational domains can be easily adapted and moved to any place in the world. Then, the paper illustrates the operational use of the modelling cascade in the frame of a major emergency exercise carried out with the firefighters and the local state authorities in Nice city (France). The exercise consisted in the fictive dispersion of radioactive materials in and out of an infrastructure. The simulations results and the main lessons learnt from the exercise are summarized in the following of the paper.

BRIEF DESCRIPTION OF THE MULTI-SCALE MODELLING SYSTEM

For the last ten years, we have developed and run a suite of models whose successive evolutions enabled the construction of a comprehensive multi-scale computational chain for atmospheric flow and dispersion. This modelling system is based on WRF weather reconstruction and forecast model and Parallel-Micro-SWIFT-SPRAY (PMSS) explicitly accounting for buildings influence on the flow and dispersion.

Originally, Micro-SWIFT-SPRAY (Tinarelli *et al.* 2013) was developed in order to provide a simplified, but rigorous CFD solution of the flow and dispersion in built-up environments in a moderate amount of time. MSS encompasses the local scale versions of SWIFT and SPRAY. SWIFT is a 3D terrain-following mass-consistent diagnostic model taking account of the buildings and providing the 3D fields of wind, turbulence, and temperature. SPRAY is a 3D Lagrangian Particle Dispersion Model able to account for the presence of buildings. The introduction of nesting in SWIFT allowed the calculation of the wind flow from the meso-scale to the local scale (Duchenne and Armand, 2010). Last years, parallel versions of SWIFT and SPRAY have been developed leading to the PMSS system (Oldrini *et al*., 2017). Moreover, a momentum solver has been implemented in PSWIFT to simulate more accurately velocity and pressure fields in built-up environments than obtained with the diagnostic flow model (Oldrini *et al*., 2016).

In practice, weather predictions at the meso-scale are produced with WRF possibly using different kinds of global input data (NCEP/GFS, ECMWF or, more recently, the AROME data of Météo France). WRF is operated in two-way nesting mode and provides the wind flow to the highest resolution (1 km) usually achievable with a meso-scale weather model. Then, PSWIFT takes over the downscaling modelling. It is run in one-way nesting mode, introducing the topography and land-use at an increasingly finer resolution.

PSWIFT is able to take account of the vegetation through a canopy model similar to the model defined for urban areas (Coceal and Belcher, 2004). Vegetation is featured by a mean height and density; a drag coefficient is applied to the fluid cells of the calculation domain where vegetation is present. Then, the final step of the downscaling consists in introducing the whole buildings at the local scale and the finest resolution (1 m). The flow in the built-up area can be approximated with analytical relations and/or fully resolved using respectively the mass-consistent diagnostic and/or the momentum version of PSWIFT.

Recent improvements in the PSPRAY model allow to deal with atmospheric dispersion not only inside the inner most, often built-up, domain, but also in all nested domains computed by PSWIFT with possible upscaling or downscaling. The principle of nesting in PSPRAY is to consider the transfer of numerical particles from a domain to another with a different level of nest in the same way as their transfer between the tiles of a large domain in which PSWIFT computations are performed in parallel.

Furthermore, PSWIFT has been coupled with Code_SATURNE in order to achieve 3D turbulent flow modelling both outside and inside buildings (among them critical infrastructures are of high interest). Then, PSPRAY can use together PSWIFT and Code_SATURNE flow input to evaluate the distribution and the possible transfers of harmful materials both indoor and outdoor. PMSS has been validated against numerous trials, especially in the frame of the COST ES1006, including idealized and realistic urban mock-ups, wind tunnel and field experiments, continuous and puff releases (Trini Castelli *et al*., 2018).

PRESENTATION OF THE EMERGENCY EXERCISE TEST-CASE

Our WRF-PMSS modelling system has been used to simulate both real accidents and other hypothetical threat scenarios. In particular, it was implemented as part of a civilian security exercise which took place on March 8, 2016. In the exercice, a hazardous material is released by a weak explosion at 8:30 am UTC from a drone hovering over a grandstand of the Allianz Riviera stadium located near the city of Nice. This test-case contains some tricky stuff to solve: a release inside a complex built-up structure, the proximity of the city with possible health consequences on the population, and a location in a coastal area with a mountainous hinterland that makes the weather situation difficult to predict.

Figure 1 and **Table 1**show the footprints and characteristics of WRF and PSWIFT calculation domains (PSPRAY domains are identical to PSWIFT ones). WRF simulation is initiated and nudged every three hours by GFS global data at 0.5° resolution (GFS analysis at noon on March 7, 2016 and forecasts of the next timeframes). To catch the meteorological phenomena inside the valley of the river Var where the stadium lies, the smoothing of topography is disabled and SRTM 3-second-arc topography used in WRF domain D04. The resolution of the very large PSWIFT domain N02 requires to split it into 7×5 tiles.

PSWIFT diagnostic version is used in the domains N01 and N02 while PSWIFT momentum version is preferred for domain N03 to model the flow in and around the complex geometry of the stadium.

Local scale domains are not only urban but have a stiff landform with a drop of 1,000 m. The topography in the PSWIFT domains is given either by the 75 m resolution BD ALTI or by the 5 m resolution RGE ALTI products of the French National Geographic Institute (IGN). Vegetation data in the domain N01 is available at 20 m resolution from the French Ministry of Ecology and shown in **Figure 2** for the region of Nice. Building data in the domain N02 comes from BD TOPO product provided by the IGN. The digital model of the stadium is built on the basis of plans and photos taken on the spot.

Figure 1. Woodlot coverage over Nice region (low percentages of woodlot coverage are light green and high percentages are dark green).

Figure 2. WRF and PSWIFT calculation domains **(a and b)** and view of the Nice stadium (inner domain) **(c)**.

Table 1. Characteristics of the WRF and PSWIFT domains.

Model	Domain	Resolution (m)	Nr of horiz. nodes	Nr of vert. nodes	Top of calculation box (m)
WRF	D01	27000	121×121	45	19300
	D02	9000	127×127	45	19300
	D03	3000	127×145	45	19300
	D04	1000	133×121	45	19300
PSWIFT	N01	75	401×401	31	3500
	N02	3	3001×2101	37	1500
	N03	1	401×401	55	1500

RESULTS OF THE EMERGENCY EXERCISE TEST CASE

Overall, the air flows over the South-East of France are complex as they are influenced by the regional Mistral wind blowing from North to South along the Rhône river valley and by sea breeze / land breeze effects with accelerations over and between the mountains. It was the case on the morning of March 8, 2016 with a variable flow around Nice city and area as shown by the illustrations in **Figure 3**. At 8:30 am UTC, the flow in the Var valley, going alongside the Allianz Riviera stadium, was oriented from North to South and met the Northeast flow from Liguria in the "bay of Angels", off Nice. At 9:30 am UTC, the wind speed in the Var valley weakened and the wind changed direction at sea North of Antibes city, with a flow directed from South to North. At 10:30 UTC, the change in the wind direction also affected the area around the Allianz Riviera stadium, with a Southwest to Northeast directional flow.

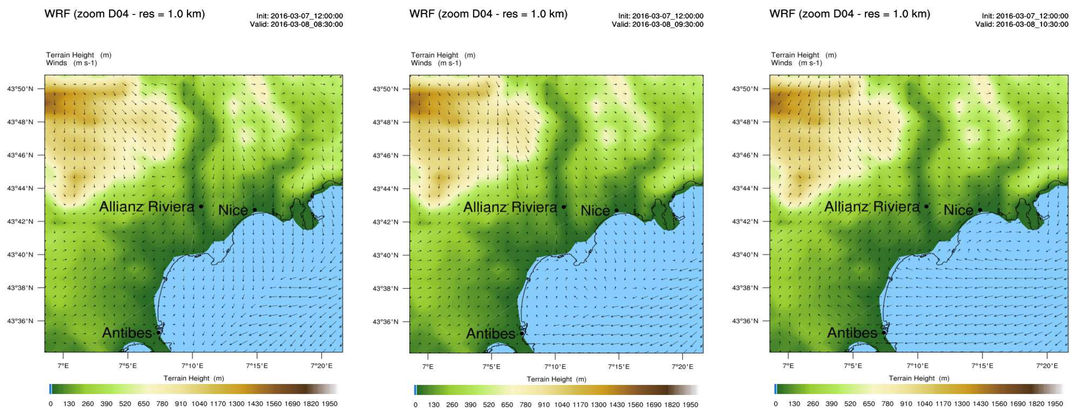


Figure 3. Topography and WRF wind field near the ground (h = 15m) for domain D04 (zoom on the Nice area).

From a much more local point of view, **Figure 4** shows horizontal and vertical cuts of the wind field on domain N03 at 8:30 am UTC, simulated by PSWIFT momentum version. The particular shape of the roof of the stadium, which extends behind the stands and envelops them, leads to fairly low wind speeds within its enclosure and to the creation of large vertical eddies above the lawn.

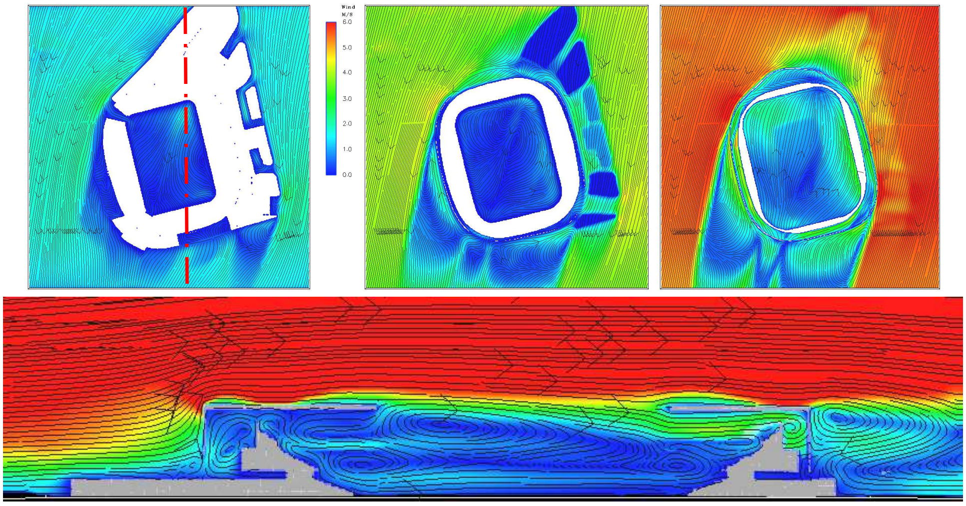


Figure 4. Horizontal and vertical cuts of the wind field on domain N03. The horizontal cuts are represented at a height of 4 m (middle of the lower rostrum), 13 m (middle of the intermediate stand) and 21 m (middle of the upper stand). The vertical section plane is indicated by the red line on the first illustration.

As for the flow field, the dispersion pattern was computed at different (spatial) scales and times after the beginning of the fictitious release to point out the complex local and global distribution of the pollutant influenced by the varying meteorological conditions, the land / sea, land-use and relief configuration with hiding effects of the buildings and recirculations around them. **Figure 5** shows the concentration field near the ground calculated on the three PSWIFT nested domains. As PSPRAY is a Lagrangian model and the volumes of the computational meshes are very different depending on the domain, discontinuities of the lowest concentrations are observed on the graphical representation of the plume at the domain interfaces between the nests. However, this is not influencial on the dispersion results.

These results of PSPRAY simulation enlighten that the harmful release is still present in the stadium enclosure and in its immediate vicinity 80 minutes after the release. The architecture of the Allianz Riviera stadium makes it a rather closed place that does not facilitate the dispersal of pollutants, and a fraction of cloud remains stuck under the roof and in the space between the roof and the back of the stands. The part of the cloud that leaves the stadium is carried South-southeast and reaches the sea, West of Nice airport, around 30 minutes after the beginning of the release. Then, the wind over the sea stretches the plume in two opposite directions. A small part of the plume heads towards the Southwest, to the city of Antibes, while the rest of the plume is driven towards the Northeast and passes over Nice airport, and further towards the city of Nice, over the neighborhoods close to the sea.

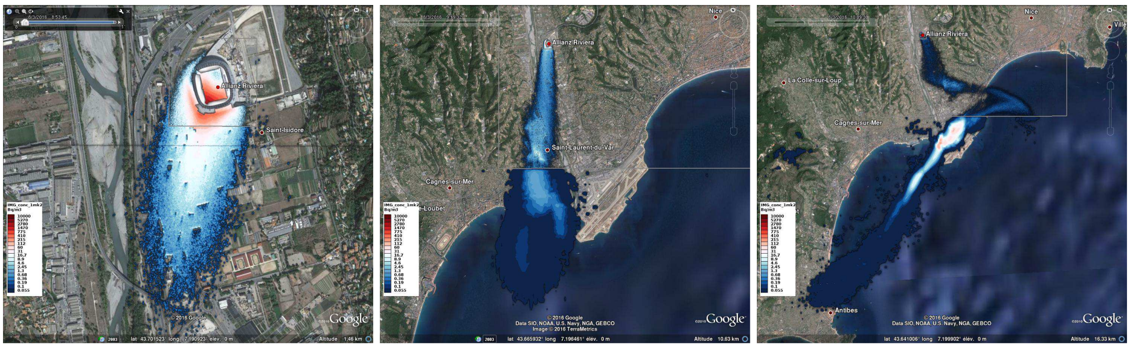
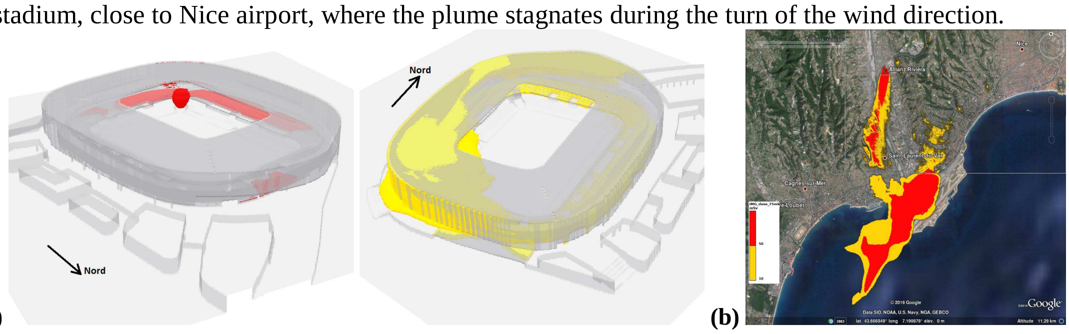


Figure 5. Concentration field after the release at different time frames (4 min, 30 min and 80 min, left to right).

This test-case illustrates the contribution of nesting in PSPRAY for long-distance tracking of the plume. Indeed, the meteorological situation (wind direction change in the morning over the ”bay of Angels”) is quite frequent at this place, and brings back from the N01 to the N02 domain a large part of the plume that came out of the N02 domain. This plume behavior would not have been observed if the simulation of atmospheric dispersion was limited to the metric resolution N02 domain and knowledge of the noxious distribution would have been degraded. An increase in the size of the N02 domain could be envisaged instead, but on one hand this would require more computing resources and, on the other hand, this would be inopportune because there is no physical phenomenon of small scale to simulate above the sea.

The health impact assessment was first carried out for the discharged quantity considered in the exercise (**Figure 6a**), then for a rejection of a larger quantity (factor of 1,000) of the noxious release (**Figure 6b**). For the small release, taking account of two typical threshold values for health effects, the consequences keep limited to the stadium enclosure. For the large release, these thresholds are exceeded even far from the stadium, close to Nice airport, where the plume stagnates during the turn of the wind direction.



(a) **(b)**

Figure 6. Consequences regarding threshold values for health effects (in red and yellow) for two releases. (a) Small release (b) Large release (factor of 1,000).

CONCLUSION AND PERSPECTIVES

The test-case presented in this paper achieves the twofold interest of demonstrating the state-of-the-art of a modelling system and applying it for the purpose of a real civilian security exercise. The suite combines WRF and PMSS in a chain cascading from the meso-scale to the local uban scale and even the inner part of infrastructures (here, a stadium facing a fictitious terrorist attack with a noxious release). The weather forecast at all scales, including the flow in the infrastructure, was ready for the exercise and the dispersion and health consequences of the release were evaluated during the first hours of the exercise.

The recent developments in PMSS, namely the nesting and parallelization of PSWIFT and PSPRAY, and the particle-splitting in PSPRAY enable simulations on extremely large domains covering an entire city at metric resolution as in the EMERGNCIES-Mediterranean project (Armand *et al*., 2017). Furthermore, the implementation of a momentum solver in PSWIFT allows to carry out reliable and precise simulations in and around complex buildings as it was done in the test-case. It is worth noticing that Code_SATURNE could be run alternatively as it is coupled with PSWIFT and PSPRAY can use flow fields of both models. Thus, the plume is accurately followed from the immediate vicinity of the source to a distance of several kilometers and visualized through a web service as presented in a companion paper (Oldrini *et al*., 2019).

To our knowledge, these multi-scale highly resolved computations are worldwide unique as they combine a huge geographical print with up to metric resolution. This is not only an exercise in style, but necessary to account for the 3D flow and dispersion in complex natural or built-up environment, and subsequently, to realistically and reliably estimate the health impact on the population and the first responders.

The simulation results produced in the course of the exercise were transmitted to the firefighters and the local state authorities who deemed the results relevant and helpful to identify the dispersion processes in the built environment, adapt the first actions of the rescue teams and anticipate the event follow-up. The maps were used all along the exercise for communication purpose, and to share a collective view during the situation updates at the command centre (as in the ”Toxic 2014” exercise, see Armand *et al*., 2015).

In the past years, our R&D effort in the field of atmospheric dispersion and health impact assessment has not only focused on the physical modelling, but also encompassed the transfer to operational applications and the adequacy of decision-support systems with the organization and missions of the civilian security. It seems to us that this approach is inescapable to promote the usage of state-of-the-art 3D models inside of computational tools accepted by practioners. Concomitantly, it contributes to the increasing interest and trust of the emergency players in up-to-date modelling to diagnose and anticipate critical situations.

Even if today, this activity is still prospective, it is likely that supercomputing will become more and more usual and benefit to first-responders and their authorities for emergency preparedness and response.

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